Hemodynamic intolerance and pericardial effusion associated with high-frequency jet ventilation during pulmonary vein isolation

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BACKGROUND High-frequency jet ventilation (HFJV) is used during pulmonary vein isolation (PVI) to increase catheter stability and improve outcomes. In prior studies, hemodynamic intolerance to HFJV was rare.

OBJECTIVES To evaluate the incidence of hemodynamic or respiratory intolerance of HFJV during PVI.

METHODS Retrospective observational analysis of consecutive patients undergoing PVI performed by 2 operators (PT, JW) at our institution between February 2019 and June 2020 who developed persistent hypotension or abnormal ventilatory parameters in association with HFJV.

RESULTS Among 194 PVIs, there were 8 cases (4%) of conversion from HFJV to conventional ventilation, 6 for refractory hypotension and 2 for persistently abnormal gas exchange. In 6 patients, including 5 of the 6 patients with refractory hypotension, a new, small pericardial effusion without tamponade was noted just after HFJV was initiated. In patients with persistent hypotension, a decrease in left ventricular filling and systolic function was frequently noted. Both the hemodynamic changes and effusion resolved almost immediately after discontinuation of HFJV. In 4 patients rechallenged with HFJV, the hypotension and/or effusion recurred quickly and again resolved immediately after return to conventional ventilation.

CONCLUSION HFJV-associated hypotension and systolic dysfunction, often accompanied by a transient pericardial effusion, is present in a small proportion of patients undergoing PVI, and resolves with cessation of HFJV. The mechanism of these changes is unclear and warrants further study.

KEYWORDS Acidosis; Alkalosis; Hemodynamic intolerance; High-frequency jet ventilation; Hypotension; Pericardial effusion; Pulmonary vein isolation

Introduction

Pulmonary vein isolation (PVI) is widely employed in the management of paroxysmal and persistent atrial fibrillation (AF). Acute procedural success depends on achieving durable ablation lesions, which has been shown to improve arrhythmia outcomes. Thoracic motion during the respiratory cycle can decrease catheter stability and various strategies have evolved to improve stability and lesion quality. One strategy involves the use of high-frequency jet ventilation (HFJV), which relies on frequent respiratory cycles and small tidal volumes, resulting in minimal respiratory motion. Because of the rapid, frequent, and low-volume respirations, inhaled anesthetic agents are not used with HFJV and sedation is achieved with only intravenous anesthesia; blood gases rather than end-tidal CO_2 are used to ensure adequate ventilation.

Since the first report of HFJV use during PVI in 2006, this approach has gained popularity in cardiac ablation procedures and has been associated with increased safety and improved procedural outcomes.[1–4] Prior studies have shown that HFJV improves short- and longer-term arrhythmia outcomes through decreased variation in contact force, greater decreases in impedance during ablation, fewer acute reconnections, and less need for repeat ablation.[1,3] In prior studies of HFJV during PVI, hemodynamic intolerance was exceedingly rare; the small proportion of patients in whom HFJV was converted to conventional ventilation had persistently abnormal gas exchange, and change in ventilation strategy during ablation was pursued for that reason. We set out to investigate rates of hemodynamic intolerance to HFJV among patients undergoing PVI.

Methods
Patient selection
Between February 2019 and June 2020, consecutive patients with paroxysmal or persistent AF undergoing PVI or left

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KEY FINDINGS

- Rapid hypotension is seen in a subset of patients on high-frequency jet ventilation undergoing pulmonary vein isolation.

- A small and reversible pericardial effusion was noted in some cases.

- Hypotension was frequently, but not always, seen in association with the pericardial effusion.

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atrial (LA) tachycardia ablation procedures performed by 2 operators (PT, JW) at Beth Israel Deaconess Medical Center (Boston, MA) were examined retrospectively. Written consent was obtained for PVI prior to the ablation procedure. This study was approved by the Beth Israel Deaconess Medical Center Institutional Review Board. The research in this study was conducted according to the Helsinki Declaration guidelines on human research. Specific consent was not required by the institutional review board for this study, as it was approved as exempt from this requirement based on its retrospective and descriptive nature.

Ablation procedure, anesthesia and ventilation strategy

Antiarrhythmic medications were generally continued periprocedurally. Anticoagulation was typically held the morning of ablation and resumed 4–6 hours after the ablation. Procedures were performed with electroanatomic mapping using the Biosense Webster CARTO system (Biosense Webster, Diamond Bar, CA). All ablation procedures were performed with radiofrequency under general anesthesia using HFJV. Femoral venous access and catheter placement occurred after induction of general anesthesia and were guided by ultrasound, fluoroscopy, and electroanatomic mapping. Single or double transseptal access was performed according to operator preference. In addition to PVI, additional ablation including posterior wall isolation, additional linear ablation, and cavotricuspid isthmus ablation was performed according to clinical need and operator preference.

At the start of the procedure, patients were intubated with standard induction medications and placed on conventional ventilation using recommended ventilator settings (volume control, tidal volume 5–7 mL/kg, respiratory rate 10–18 breaths/min, positive end-expiratory pressure 0–5 mm Hg) to maintain end-tidal CO_2 between 35 and 40 mm Hg. Anesthesia was maintained using inhalational anesthetic with minimum alveolar concentration value 0.7–1.0. Upon switching to HFJV (Monsoon III Jet Ventilators; Acutronic Medical Systems AG, Hirzel, Switzerland), anesthesia was maintained with total intravenous anesthesia using propofol 50–200 mcg/kg/min and remifentanil 0.05 and 0.40 μg/kg/min infusions. HFJV was delivered with a driving pressure of 18–24 mm Hg, inspiratory time 30%–40%, frequency

(analog of respiratory rate) of 120 cycles/min, FiO2 of 60%–100%, and 40%–70% humidity. Ventilation was monitored and guided using primarily venous blood gases obtained from peripheral venous catheter sheaths. The target ventilation parameters included peripheral venous CO_2 35–55 mm Hg. Management of CO_2 on HFJV was performed by the anesthesiologist primarily by changes in driving pressure, inspiratory time, or frequency. HFJV could be initiated before or after transseptal access per operator preference but was typically initiated just after transseptal puncture in the majority of cases. In the event of worsening gas exchange, driving pressure or respiratory rate was adjusted and a repeat blood gas obtained 15 minutes later. The decision to discontinue HFJV was determined by the individual operator in conjunction with anesthesia based on clinical judgment for persistent hypotension, or for refractory alkalosis or acidosis.

Hemodynamic assessment

Phenylephrine was the vasopressor of choice with goal systolic blood pressure (SBP) >100 mm Hg (and/or mean arterial pressure >60 mm Hg). Additional boluses of phenylephrine in addition to titration of the continuous infusion were administered for a decrease in SBP of more than 20 mm Hg. Serial blood pressure monitoring was obtained primarily through noninvasive measurement every 3–5 minutes. Intracardiac echo was used to assess anatomy, guide ablation, and monitor for procedural complications.

Statistical analysis

Continuous variables are expressed as means ± standard deviations and categorical variables as percentages. Statistical comparison was performed using the Student t test for continuous measures and the χ^2 test for categorical variables. Stata version 15.1 (StataCorp, College Station, TX) was used for statistical analysis.

Results

Among 194 cases, there were 8 cases (4%) of conversion from HFJV to conventional ventilation; 6 due to refractory hypotension and 2 due to abnormal gas exchange. The decision to abandon HFJV was made by the operator in conjunction with the anesthesiologist at the time of the ablation. Although there were no absolute criteria, among those in whom HFJV was abandoned for hypotension, the SBP at the time of conversion to conventional ventilation was <70 mm Hg, with a mean drop of 50 mm Hg that occurred within 5 minutes of HFJV initiation and persisted despite phenylephrine boluses and increases in phenylephrine infusion. The mean bolus of phenylephrine administered in these patients was 250 mcg accompanied by an average increase in baseline phenylephrine infusion of 0.2 mcg/kg/min. In 1 case a second pressor, ephedrine, was added to phenylephrine prior to abandonment of HFJV. The average time between initiation of HFJV and discontinuation was 23 minutes and in all cases, the time between the most recent bolus of sedation and onset of hypotension was more than

Table 1   Characteristics of patients with significant hypotension or abnormal gas exchange

	Reason for HFJV abandonment							
	HoTN	Alkalosis	HoTN	HoTN	HoTN	HoTN	Acidosis	HoTN
Patient	1	2	3	4	5	6	7	8
Age (years)	71	77	62	81	63	71	70	43
Sex	M	F	F	F	M	M	M	F
BMI (kg/m^2)	25.1	35.0	24.5	24.2	27.2	21.5	30.6	28.7
Baseline EF (%)	55	60	60	65	60	20	55	60
AF type	PAF	peAF	PAF	PAF	peAF	peAF	peAF	PAF
HTN	N	Y	N	Y	N	N	Y	N
DM	N	N	N	N	N	N	N	N
CAD	N	N	N	N	Y	N	Y	N
HF	N	Y	N	Y	Y	Y	Y	N
Sleep apnea	Y	Y	N	Unknown	Unknown	Unknown	Y	Unknown

AF = atrial fibrillation; BMI = body mass index; CAD = coronary artery disease; DM = diabetes; EF = ejection fraction; F = female; HF = heart failure; HFJV = high frequency jet ventilation; HoTN = hypotension; HTN = hypertension; M = male; N = no; PAF = paroxysmal atrial fibrillation; peAF = persistent atrial fibrillation; Y = yes.

60 minutes. In the 6 patients in whom HFJV was abandoned for hypotension, the transition to conventional ventilation occurred prior to commencement of ablation. Among those with refractory hypotension, the mean age was 68.6 ± 10.4 years (range 43–81 years), 50% were female, body mass index (BMI) was 25.6 ± 3.4 kg/m^2, and mean LA pressure was 12 mm Hg (range 3–21 mm Hg). Among the 6 patients with hypotension, 1 patient (17%) had severe left ventricle (LV) dysfunction with left ventricular ejection fraction (LVEF) 20%, 2 patients (34%) had persistent AF, 1 (17%) had hypertension, 3 (50%) had a history of clinical heart failure, 3 patients (50%) had documented sleep apnea, and 4 patients (67%) were undergoing first-time PVI (Table 1). In 5 of 6 patients with refractory hypotension, a visible change in systolic function related to decreased LV filling was noted on intracardiac echo (Video 1, Supplemental Material).

There were 6 cases in which a new, small pericardial effusion without tamponade was observed in association with HFJV (Table 2 and Figure 1). The transient effusion was noted in patients with and without hypotension. The effusion was noted only around the right ventricle in 2 cases, only around the LV in 3 cases, and around both right ventricle and LV in 1 case. An effusion was noted in 5 of 6 patients with refractory hypotension and in 1 patient without clinically significant

hypotension. In all patients, the hypotension and effusion both resolved immediately after stopping HFJV (Video 1, Supplemental Material). Four patients were rechallenged with HFJV, with recurrence of rapid-onset hypotension and effusion, which again resolved immediately after return to conventional ventilation. In each case, the decrease in blood pressure was more rapid and pronounced upon rechallenge with HFJV. In patients with decreased LV function on intracardiac echo, the systolic function returned to baseline upon stopping HFJV. In the patient without hypotension noted to have a small pericardial effusion, HFJV was temporarily halted with resolution of the effusion and the patient was monitored for 30 minutes before reinitiation of HFJV and continuation of the procedure. There was no increase in the size of the effusion, with therapeutic activated clotting times maintained throughout the procedure.

Among the 2 cases of persistently abnormal blood gases, HFJV was abandoned owing to significant respiratory acidosis (venous blood gas pH 7.30, pCO$_2$ 60) in 1 and respiratory alkalosis (venous blood gas pH 7.62, pCO$_2$ 32) in another, despite appropriate changes in ventilation parameters (Table 2). In all cases where HFJV needed to be stopped, ablation was successfully completed on conventional ventilation without further hemodynamic or respiratory disturbance.

**Table 2**   Hemodynamic and respiratory parameters

Patient	Baseline BP	BP after HFJV[‡]	Decrease SBP mm Hg	Effusion	Effusion location	Opening LAP	pCO2	Reason for abandoning HFJV
1[†]	125/65	63/24	62	Y	LV	3	45	HoTN
2	178/127	110/60	68	Y	LV	21	30	Alkalosis
3	110/70	78/50	32	Y	RV	12	-	HoTN
4	125/50	70/50	55	Y	RV	9	-	HoTN
5[†]	129/98	65/52	64	N	-	7	-	HoTN
6[†]	140/80	75/60	65	Y	RV, LV	17	31	HoTN
7	110/80	90/51	20	N	-	11	60	Acidosis
8[†]	130/80	65/50	65	Y	LV	13	33	HoTN

Yellow bar = effusion without hypotension; green bar = hypotension without effusion.

BP = blood pressure; HFJV = high-frequency jet ventilation; HoTN = hypotension; LAP = left atrial pressure; N = no; LV = left ventricle; RV = right ventricle; SBP = systolic blood pressure; Y = yes.

[†]Rechallenged with HFJV.

[‡]After treatment with vasopressors.
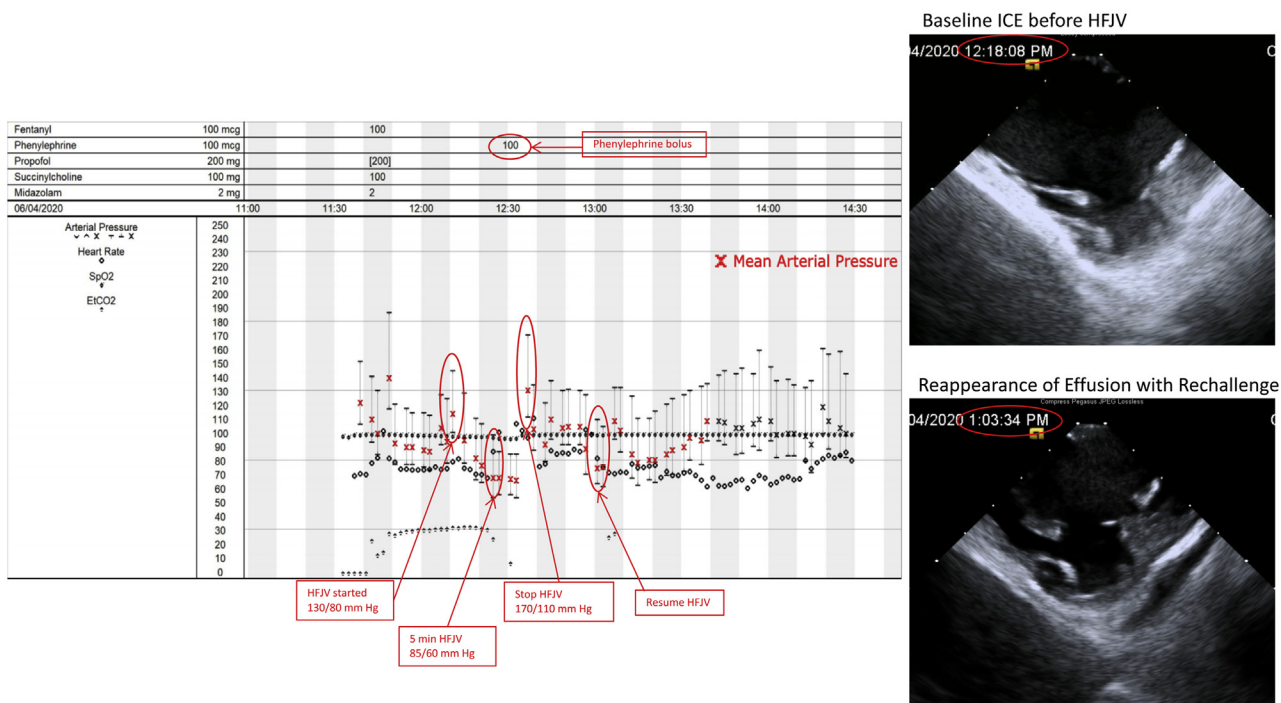
Figure 1 Blood pressure decrease and corresponding effusion. Anesthesia chart and intracardiac echocardiogram (ICE) images. HFJV = high-frequency jet ventilation.

When compared with patients in whom PVI was completed on HFJV without significant hemodynamic or respiratory intolerance, patients who did not tolerate HFJV had lower BMI and LVEF than those who tolerated HFJV (Table 3).

Discussion

Our study found that in a small proportion of patients undergoing PVI, HFJV was associated with persistent hypotension and frequently, a transient pericardial effusion. To our knowledge, this has not been previously described. In patients with hemodynamic intolerance of HFJV, rechallenge provoked rapid recurrence of hypotension and effusion. These changes resolved immediately upon stopping HFJV.

We found hemodynamic intolerance to occur more frequently in our population than previously described. One prior case report documented extreme hypotension on HFJV during PVI that rapidly improved with conventional

Table 3 Comparison of patients with continuation vs abandonment of HFJV

	HFJV continued n = 186		HFJV abandoned n = 8		
	N or mean	% or SD	N or mean	% or SD	P value
Age (years)	63.5	9.7	68.6	10.4	.11
Male	123	65.8	4	40	.10
BMI (mg/kg²)	29.9	5.8	25.6	3.4	.02
LVEF (%)	55	9.4	48	15	.03
Paroxysmal AF	97	52	4	40	.46
LA pressure	13.6	5.3	12	5.6	.39

AF = atrial fibrillation; BMI = body mass index; HFJV = high-frequency jet ventilation; LA = left atrial; LVEF = left ventricular ejection fraction.

ventilation.[5] This patient had an LA pressure of 7 mm Hg, BMI of 29.5 kg/m², and experienced profound hypotension despite 1 liter of intravenous fluid and phenylephrine boluses. As noted in our study, reinstitution of HFJV precipitated recurrent hypotension that was more pronounced than the initial decrease in blood pressure.[5] Among the other published studies of HFJV for PVI, a single case of hemodynamic intolerance requiring conversion to conventional ventilation has been reported.[2] In this study, a greater proportion of patients required vasopressors in the HFJV group compared to standard ventilation, but the mean dose administered was similar between the 2 groups. Neither study described a pericardial effusion on intracardiac echo. No additional cases of conversion to conventional ventilation due to hypotension were reported among the remaining studies of HFJV for PVI.[1–4,6]

Mechanism of hypotension

The mechanism by which HFJV leads to hemodynamic intolerance is not clear. In our study, the development of hemodynamic intolerance did not appear to be related to age, sex, AF status, LA pressure, or ventilatory metrics. However, BMI was significantly lower among those who developed hypotension requiring conversion to conventional ventilation compared to those who tolerated HFJV (Table 3). LVEF was also lower in those intolerant of HFJV, though this was driven by a single patient with a severely reduced LVEF. Prior studies have found that HFJV induces a decrease in LA volume without a corresponding change in LA pressure.[4] Mechanistically, this may result from the compressive effect of persistently inflated lungs during HFJV combined with elevated intrathoracic pressures

and the absence of an increase in LA pressure may be the result of decreased intrathoracic blood volume. These hemodynamic changes with HFJV may explain the profound decrease in SBP accompanied by a decrease in systolic function and decreased filling on intracardiac echo that was observed.[4]

Prior studies have found varying effects of high-frequency ventilation on cardiac output. Studies of pediatric patients undergoing surgical correction of congenital cardiac anomalies documented no decrease in cardiac output with high-frequency ventilation,[7–9] while others note improvement in cardiac output and systolic function on HFJV.[10] In animal models, HFJV has been associated with negative inotropy and decreased end-diastolic pressure and volume.[11] In our study, titration of pressors and fluid resuscitation did not overcome the hypotension in this small group of patients. HFJV during catheter ablation requires specialized equipment and has unique anesthesia requirements requiring specialized clinical expertise. Our findings may suggest that in patients with lower BMI, perhaps adjustment of HFJV settings to account for greater changes in thoracic impedance or other hemodynamic effects in patients with lower BMI may be required in addition to pressor support.

Transient pericardial effusion

To our knowledge, the presence of a transient pericardial effusion associated with HFJV has not been described. Remarkably, the appearance of the effusion was reproducible and immediate with initiation of HFJV. Similarly, resolution occurred almost instantly and before any change in pCO_2 or ventilatory status. The rapidity of onset and resolution may represent redistribution of pericardial fluid as a result of a change in intrathoracic pressures with HFJV. However, thorough examination with intracardiac echo did not reveal a preexisting effusion in these patients. In the video, accumulation of fluid is seen both anteriorly and posteriorly, which is less consistent with redistribution of pericardial fluid due to positional changes of the heart with HFJV (Video 1, Supplemental Material). The small size and transient nature of the effusion may suggest a transudative etiology resulting from a rapid increase in intrathoracic pressures in patients with particular characteristics such as elevated pulmonary pressures. There was 1 patient with hemodynamic intolerance who did not develop an effusion and 1 patient with an effusion who did not develop hypotension. Thus, it is not clear whether the mechanism underlying the hypotension is the same as that precipitating the effusion. Further study of this phenomenon is warranted.

Overall, abnormal gas exchange was an infrequent cause of HFJV intolerance in our study. HFJV was abandoned owing to abnormal gas exchange in only 1% (2 of 194 cases) of patients. Prior data reported a 6%–7% incidence of conversion from HFJV to conventional ventilation owing to abnormal gas exchange.[3,6] Previous work has suggested an association with BMI and CO_2 retention for procedures using HFJV[12] and lower BMI was predictive of hemodynamic intolerance in our study. Thus, standard baseline settings for HFJV may need to account for lower BMI values. We were not able to assess this relationship in our study, as adjustments in HFJV settings were prompted by abnormal gas exchange but not hypotension. As such, adjustments to HFJV settings were not attempted in cases of hemodynamic intolerance. With regard to acidosis vs alkalosis, a prospective analysis of 84 patients undergoing PVI found an equal incidence of respiratory acidosis and alkalosis (19% and 20%) among those on HFJV, though no patients in that study required conversion to conventional ventilation.[2]

Though the co-occurrence of 2 rare developments, hypotension and transient effusion, raises the possibility of a common underlying process, it is not clear whether they are directly linked, as 1 of the 6 patients with hypotension did not develop an effusion and 1 of the 6 patients with an effusion did not develop hypotension. To better understand this relationship requires prospective evaluation of the effects of HFJV in a larger population.

Our findings emphasize the importance of understanding the mechanism of hemodynamic effects of HFJV and the need for specific clinical expertise in anesthesia for HFJV. It is possible that patients with lower BMI or low LVEF may not be optimal candidates for HFJV, though prospective data are required to further evaluate this question. The ability to tolerate HFJV has consequences for procedural planning; hypotension or abnormal gas exchange necessitating changes in driving pressure or frequency results in shifts in electroanatomic maps. These shifts prolong procedure duration by requiring additional mapping, and inaccurate maps increase the risk of ineffective ablation and present potential risks related to ablation complications. Ideally, prospective identification of individuals intolerant to HFJV would allow for more efficient and safer procedural planning and, perhaps, avoidance of HFJV in selected cases.

Study limitations

The data represent a retrospective observational sample from 2 operators. The decision to abandon HFJV owing to hemodynamic intolerance was a clinical decision made at the time of the ablation. Nonetheless, this clinical situation was noted by 2 independent operators over a 16-month timeframe after 8 combined years of independent practice, and reflected discussion with the anesthesiologist. Furthermore, HFJV is universally used at our institution for all LA ablation procedures. Over the past year, the practice at our institution has moved to earlier initiation of HFJV during PVI, typically after catheter placement and prior to transseptal puncture. However, during the study period, HFJV was frequently initiated after transseptal puncture and thus, it is difficult to determine whether timing of HFJV initiation affected our findings.

Conclusions

This study describes a subset of patients in whom HFJV was associated with rapid-onset hypotension. In the majority of these patients, a transient pericardial effusion that developed very quickly after initiation of HFJV was noted. It is important to recognize that HFJV can be a reversible cause of

profound hypotension and pericardial effusion during PVI. We found that the hemodynamic changes and effusion resolved immediately with cessation of HFJV. Further study with a larger number of patients is needed to identify the mechanism of the hemodynamic effects of HFJV and to prospectively identify patients who may not be optimal candidates for HFJV during catheter ablation.

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Disclosures

The authors have no conflicts to disclose.

Authorship

All authors attest they meet the current ICMJE criteria for authorship.

Patient Consent

Written consent was obtained for PVI prior to the ablation procedure. Specific consent was not required by the institutional review board for this study, as it was approved as exempt from this requirement based on its retrospective and descriptive nature.

Ethics Statement

The research in this study was conducted according to the Helsinki Declaration guidelines on human research. This study was approved by the Beth Israel Deaconess Medical Center Institutional Review Board.

Appendix
Supplementary data

Supplementary data associated with this article can be found in the online version at https://doi.org/10.1016/j.hroo.2021.05.005.

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